Comparative Machining characteristics studies on SS 304 using coated and uncoated brass wire through Wire EDM

T. Suresh, K. Jayakumar, G. Selvakumar, S. Ram Prakash

The growing demands for high surface finish with complex shape geometries, traditional machining is now being substituted by unconventional machining processes. Wire Electric Discharge Machining (Wire EDM) is one of the unconventional metal cutting processes. Stainless Steel 304 (SS 304) is widely used in Aerospace, Medical, Electronics and Semiconductor, Tool and Die making industries. However, during traditional machining of SS 304, industries are facing numerous difficulties. In view of the exceeding purposes and challenges in traditional machining of SS 304, the present research investigates the effect of Wire EDM parameters such as Current (I), Gap Voltage (V), Pulse on time (Ton), Pulse of time (Toff) with two different electrode wire materials (Brass and Zinc coated brass) on SS 304 material. After machining, Surface roughness (SR), microhardness (HV) of the machined surface and thickness of recast layer were measured to assess the machinability of the SS 304. Wire EDM experiments have been performed using a CNC Wire EDM machine as per Taguchi's L_{18} orthogonal design. Coated and uncoated brass wires of ϕ 0.2 mm were taken as wire electrode materials.
From the study, coated brass wire has shown the high surface finish and hardness than uncoated brass wire. Furthermore, the recast layers of the machined surfaces were analyzed for both wire electrodes using the SEM images. Analysis of variance (ANOVA) was carried for finding significant parameter for all output responses. Finally, grey relational analysis (GRA) was applied to find overall optimized process parameter mixture for maximization of hardness and minimization of SR.

PAROLE CHIAVE: SS 304, WIRE EDM, SURFACE FINISH, MICROHARDNESS, RECAST LAYER THICKNESS, BRASS AND ZINC COATED BRASS WIRE ELECTRODE, GRA

INTRODUCTION

SS 304 is an austenitic and nonmagnetic steel material and has outstanding corrosion battle and forming characteristics due to high ductility. It is mainly used in cryogenic vessels, kitchen wares, heat exchangers, surgical equipment, etc (1). On the other hand, most of these components need diverse metal cutting processes to manufacture the desired shape with high accuracy. Still, through conventional machining of SS 304, industries are encountering many troubles for instance high tool wear because of reduced thermal conductivity and high BUE affinity on the tool side.
Wire EDM is an alternate thermo electric machining process, which is widely to cut hard to machine materials like steels, titanium and other superalloys. Aerospace, automobile, and electronic industries often use Wire EDM process to cut intricate shapes and designs, fragile geometries, dies, molds, etc. Several researchers have started attempting to machine SS 304 and other steels using Wire EDM process as well as predicted optimal parameter combination for achieving different and high machinability responses.

T. Suresh, K. Jayakumar, G. Selvakumar, S. Ram Prakash
Department of Mechanical Engineering, Sri Sivasubramaniya Nadar College of Engineering, Kalavakkam, Chennai-603110, India

Corresponding author: *kjayakumar@ssn.edu.in

Ugrasen et al. (2) investigated the effect of process parameters of Wire EDM on SS 304 with molybdenum as an electrode. The parameters considered were Ton, Toff, I and bed speed and their effect on MRR, electrode wear, dimensional Error and surface roughness were analyzed in detail. Optimized parameter setting was identified to improve the machinability during Wire EDM process. D2 steel was machined by Wire EDM process by Mahapatra et al. (3) using Zinc coated Cu wire of ϕ 0.25 mm. In this work, they optimized current, pulse duration, frequency, wire speed, tension and dielectric flow rate for maximizing of MRR and minimizing of surface roughness in WEDM process using Taguchi and Genetic Algorithm.

Durairaj et al. (4) analysed the effect of process parameters in WEDM of SS 304 using Taguchi Grey relational grade. They recommended optimized input parameter combinations (Ton, Toff, V and wire feed) to get least amount of surface roughness and kerf width. Bijo Mathew et al. (5) conducted Wire EDM studies on SS 304 to optimize MRR, Ra and dimensional deviation using Taguchi grey relational analysis using ϕ 0.25 mm brass wire.

Harinath Gowd et al. (6) studied the effect of input parameter Ton, Toff, wire tension and water pressure on Roughness and MRR while machining SS 304 using ϕ 0.25 mm brass wire. Muhammad Azam et al. (7) conducted experiments to find out the WEDM process parameters which contribute to recast layer in high-strength low-alloy (HSLA) steel using molybdenum wire with ϕ 0.2 mm.

Asfana Banu et al. (8) used micro dry wire EDM (μDWEDM) to machine SS 304 with smooth and stable manner. They varied and optimized types of dielectric fluid, its pressure, polarity, threshold, wire tension, speed, feed rate, voltage, and capacitance using tungsten wire for smooth machining of SS 304. The same researchers continued the μDWEDM process to machine SS 304 effectively recently using the same tungsten wire of ϕ 0.07 mm as per one factor at a time and design of experiments (9). Kashif Ishfaq et al. (10) used GRA for multi objective optimization in favour of maximization of cutting speed and minimization of surface roughness and kerf width during WEDM of SS 304.

Therefore, research work on Wire EDM of SS 304 has been carried out continuously to investigate the consequence of process parameters on a range of performances namely surface roughness (SR) and kerf width. But the characteristics, formation of recast layer and its hardness on SS 304 along with SR using coated and uncoated brass wires has not reported yet. Also, less works has been carried out using the application of GRA on multi objective optimization of different process parameters on SS 304 using Wire EDM process.

EXPERIMENTAL DETAILS

Workpiece, Machine and Process parameters

SS 304 block with 300 x 300 x 25.4 mm size was taken for the comprehensive Wire EDM studies. Machining was carried out on a Smartcut 2530 CNC Wire cut EDM machine with maker of Ratnaparkhi Electronics Ind. Pvt Ltd. De-ionized water was taken as dielectric medium since it has low viscosity, electrical conductivity and carbon-free medium.

Machining experiments were carried out using brass and zinc coated brass (stratified) wires with 0.2 mm diameter with vertical configuration. Compared to Cu wire electrode, adding Zinc to brass wire electrode offers extremely high electrical conductivity, tensile strength, low melting point and cost. Owing to complications in manufacturing brass wire with any concentration value of Zn, coated brass wire is created. The coated wire is a combination of Cu/brass core, and it is coated with Zinc to support efficient dielectric flushing and easy spark development (11). Most of the research works used wire with ϕ of 0.2, 0.25 and 0.3 mm. In this work, ϕ 0.2 mm was used since less diameter wire has higher cutting speed consequently increases the MRR (12).

After conducting trail experiments and from literature, the following process parameter, their levels and range (listed in table 1) were selected for machining the SS 304 material. Wire feed and tension were kept as constant as 3 m/min and 25 N respectively. Size of each specimen after Wire EDM process was in square prism with the dimension of 5 x 5 x 25.4 mm. Figure 1 demonstrates the Wire EDM setup with machining of SS 304 and figure 2 shows the 18 pieces taken out after Wire EDM from SS 304 block.

Tab.1 - Process parameters and levels

Sl. No	Machining process parameter	Level 1	Level 2	Level 3
1	Wire material	Zn coated brass	Uncoated Brass	-
2	Pulse on Time- Ton (μs)	105	110	115
3	Pulse off Time-Toff (μs)	25	35	45
4	Peak current (Amp)	1	3	5
5	Gap Voltage (volt)	20	30	40

(a)

(b)

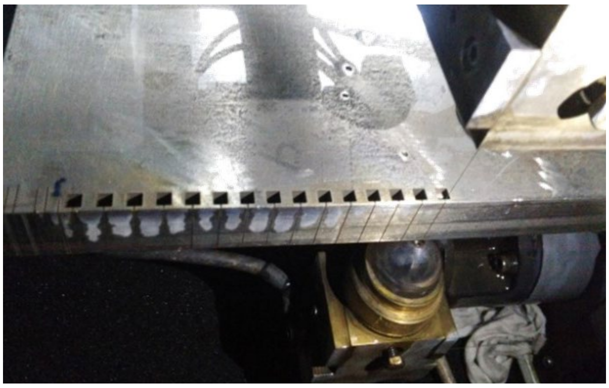
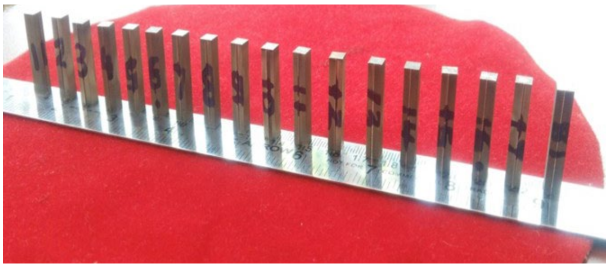


Fig.1 - a. Wire EDM facility. b. machining of SS 304 Workpiece



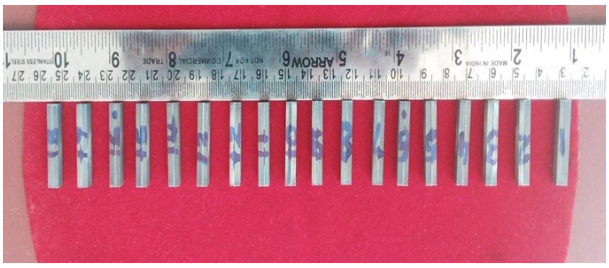


Fig.2 - 18 samples (5 x 5 x 25 mm) after Wire EDM (a) vertical position (b) horizontal

EXPERIMENTAL DETAILS

After Wire EDM, average surface roughness values (Ra) on the machined surfaces (opposite to the direction of machining in 2 flat sides out of 4 sides of the square prism) were measured using Surface roughness tester (Mitutoyo Surf test 210). Measuring parameters used are: cut off length (λc) of 0.8 mm and number of samples (n) as 5 using diamond tip of 5 μm diameter. Average of three readings taken at different places was considered as final result. Fig. 3 illustrates the measurement of surface roughness on the machined sample.

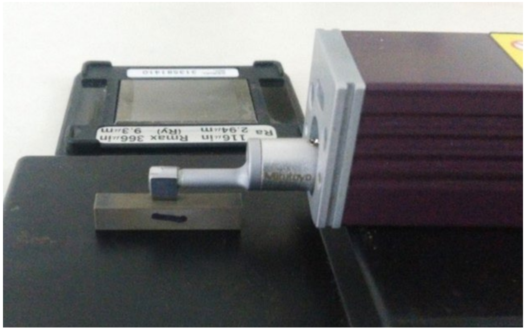


Fig.3 - Surface roughness measurement

Microhardness of the machined surfaces of the samples was measured using micro vickers hardness tester (Model: NOVA 130-240) with load of 1 kg using diamond indenter for 30 seconds. Average of three readings was considered. In order to trim down the number of experiments for these 5 factors with 3 levels; Taguchi's L_{18} orthogonal array was selected. Out of 18 experiments, 9 experiments were conducted using brass wire. Remaining 9 were conducted using zinc coated brass wire to analysis the effect of wire coating. Experimental runs and their results are listed in Table 2. SEM images were taken to measure the recast layer thickness of the machined surfaces which is having high, low and average Ra value.

Tab.1 - Process parameters and levels

S. No.	A: Wire material	B: Ton (µs)	C: Toff (µs)	D: Current (A)	E: Voltage (V)	Surface roughness Ra (µm)	Hardness (HV)
1	Zn coated Br (1)	105	25	1	20	1.782	199
2	Zn coated Br (1)	105	35	3	30	2.091	194
3	Zn coated Br (1)	105	45	5	40	2.042	193
4	Zn coated Br (1)	110	25	1	30	2.789	179
5	Zn coated Br (1)	110	35	3	40	2.757	188
6	Zn coated Br (1)	110	45	5	20	3.108	202
7	Zn coated Br (1)	115	25	3	20	3.432	189
8	Zn coated Br (1)	115	35	5	30	2.681	186
9	Zn coated Br (1)	115	45	1	40	2.836	198
10	Uncoated Brass (2)	105	25	5	40	2.235	188
11	Uncoated Brass (2)	105	35	1	20	2.205	193
12	Uncoated Brass (2)	105	45	3	30	2.303	179
13	Uncoated Brass (2)	110	25	3	40	2.668	201
14	Uncoated Brass (2)	110	35	5	20	2.786	191
15	Uncoated Brass (2)	110	45	1	30	2.508	176
16	Uncoated Brass (2)	115	25	5	30	2.890	190
17	Uncoated Brass (2)	115	35	1	40	2.823	188
18	Uncoated Brass (2)	115	45	3	20	3.016	203

RESULTS AND DISCUSSIONS

The effect of the five selected controllable factors on Wire EDM responses is shown in figure 4 to 5. The analysis was carried out using the MINITAB 19 software.

Effect of process parameter on Surface roughness

Average surface roughness (Ra) value increased from 1.782 to 3.432 µm with raise in Current and Ton. This is because, increase in current and Ton time, results in high thermal and tensile pulling load on the workpiece in inter electrodes gap (13). Bigger-sized voids and powerful deep and wider surface cracks were as well formed with a raise in current and Ton. Increase in Toff reduced the Ra value due to effective flushing of melted workpiece debris (14). During the raise in voltage, the discharge gap enlarges which means the concentration of spark imposes on the surface of the workpiece (w/p) is low and creates small craters leading to lower Ra on the surface of the workpiece (15).

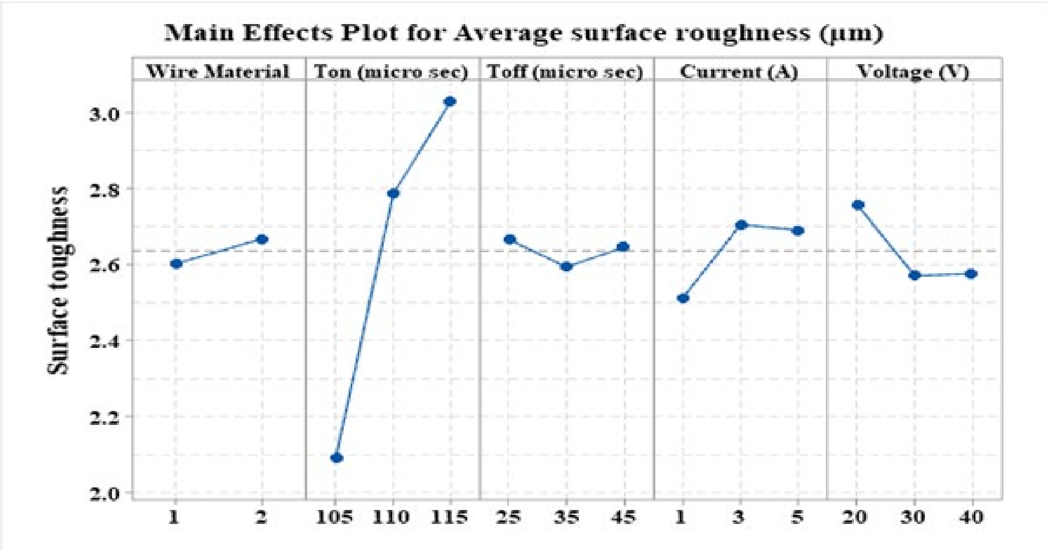


Fig.4 - Main effect plot for surface roughness

In zinc coated brass wire, the external zinc coating has lower melting point compared to the core brass. Therefore, vanishing of this outer coated layer results in enlarged the size of gap and consequently origins enhanced removal of debris. Efficient flushing improved the surface finish of the machined part. From the 18 experiments, surface roughness value obtained from coated wire electrode shows nearly 3% improvements in surface finish than uncoated wire.

Analysis of Variance (ANOVA) was used to look into which process parameter notably changes the surface roughness. It was found that Ton (83%) and current (6%) were identified as dominant factors for Ra value than other two factors.

Effect of process parameter on microhardness

Figure 5 shows the effect of process parameter on microhardness and microhardness of the machine sample surface increased from 176 HV to 203 HV during Wire EDM process due to repetitive heating and cooling.

Hardness produced on the workpiece material by coated brass wire is 1.1% higher than uncoated wire. Coated wire provides higher flushing (11) than uncoated wire since the easy evaporation of outer coated layer results in increase in gap size which caused the workpiece material to cool rapidly thus increased the hardness. Hardness increased for increase in Current, Ton and Toff time this is because of simultaneous increase in heat energy to the workpiece and fast cooling effect on the outer layer of the work surface.

As the voltage increases, the gap between the wire electrode and workpiece increased thus causes less impact of heat energy on to the work surface. Heating with low temperature and then more cooling effect on the work surface reduced the increase in hardness when the voltage is increased (7).

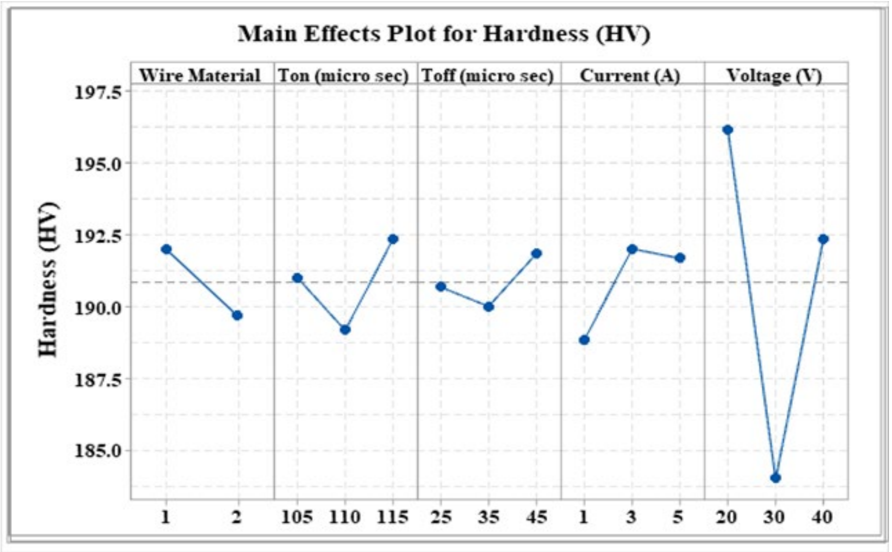


Fig.5 - Main effect plot for microhardness

The results of ANOVA show that the factors voltage (54%) and current (12.5%) were the most dominant factor that affects the microhardness.

The SEM micrographs were taken on the machined surface of the samples for the experiment 5 and 13 with same magnification of 3500X to correlate the mechanical properties and microstructure since microstructure and mechanical properties in metals are closely coupled. Since the sample from experiment number 5 and 13 has used same power input values (Ton = 110 µs, Current = 3 A and Voltage = 40 V) with varying Toff time using Zinc coated brass wire and uncoated brass wire respectively. But the sample 13 has high hardness value than 5.

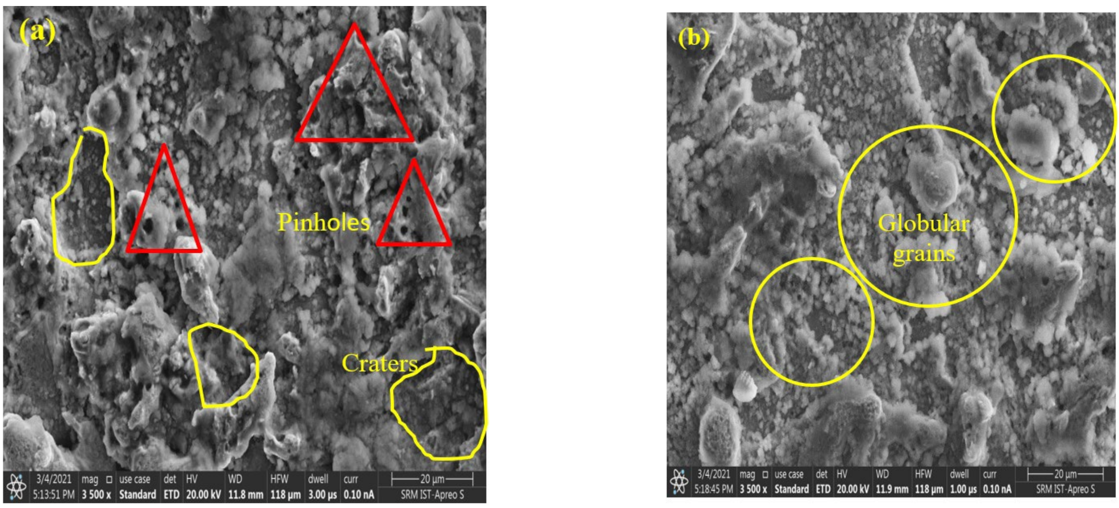


Fig.6 - Microstructure of the machined surface (a) 5th experiment with Zn coated brass wire (b) 13th experiment with uncoated brass wire.

The Zn coating in the coated wire melts evaporates easily and increased gap size thus causes better debris removal compared with uncoated wire. Consequently, increased the material removal along with pinholes, larger craters and non-spherical agglomerates which were observed (16) in the image of the microstructure shown in figure 6.a with triangles and freeform shapes respectively. More pinholes and craters were observed in microstructure image of figure 6.a. compared with 6.b. These surface irregularities manifest lower resistance to plastic deformation which reduces the hardness value. In figure 6.b, the formation of globular grain structure on the surfaces of machined region were observed (indicated with circular shapes) for the 13th experiment that makes the surface as even resulting in increased hardness on the surface of the workpiece.

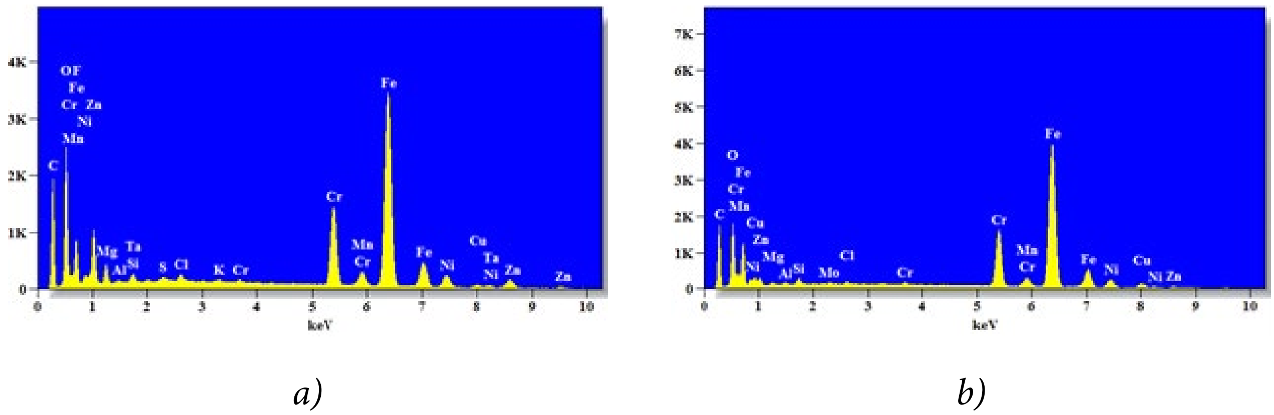


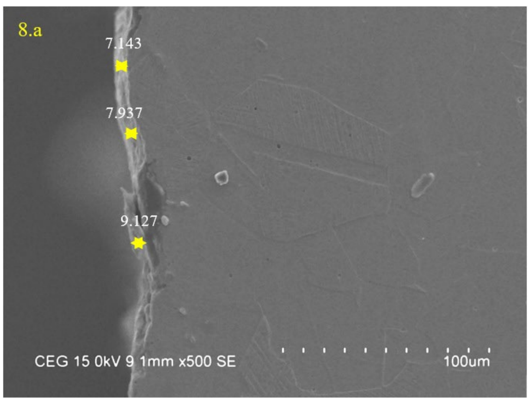
Fig.7 - Energy Dispersive X-ray (EDX) analysis (a) 5th experiment (b) 13th experiment.

The machined surface topography was analyzed through EDX analysis for the 5th and 13th experiment and is shown in Figure 7.a and 7.b. For 13th experiment, the weight % of major elements such as Cr (12%), Fe (52.3%), Ni (4.6%) and Cu (2.59%) are more than 5th experiment (Cr-11%, Fe-44.2%, Ni-4.15% and Cu-1.1%) after WEDM which also enhanced the hardness value.

Analysis of surface recast layer thickness

During Wire EDM process, dielectric fluid is continuously fed closer to the space between workpiece and wire electrode to clear the eroded metal. As a result, the top surface is quenched, and un-flushed debris is resolidified at faster level because of high thermal conductivity of dielectric fluid. This layer is known as resolidified/recast layer. This layer is normally of hard, brittle and moreover, this layer has a changed microstructure, tensile stresses, microcracks, impurities and other unwanted features which can pilot to early component failure. Thus, formation of recast layer and its thickness should be monitored and controlled.

SEM images were taken on the surface of the machined SS 304 sample after following standard polishing and etching procedure to analysis the thickness of the recast layer formed. Out of 18 experiments, SEM images were taken for selected machined surfaces like experiments which have high, low and medium Ra value. Following SEM images (Figure. 8a, 8b, and 8c) shows the measurement of recast layer thickness (RLT).



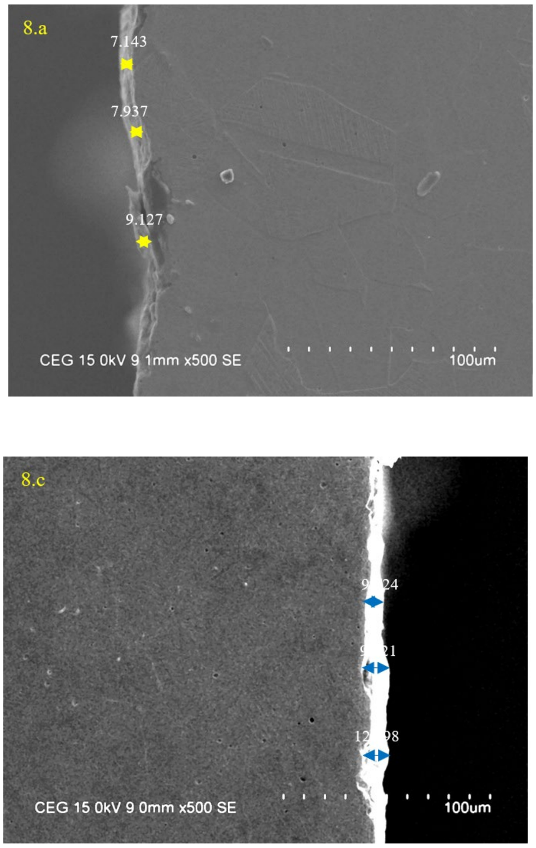


Fig.8 - Recast layer thickness of the machined samples (a) for Exp. no. 1 – average RLT-8.069 μm (b) Exp. no. 7– average RLT-14.815 μm (c) Exp. no. 13– average RLT-10.714 μm.

The figure 8.a shows the surface which has low Ra obtained from 1st experiment and its average RLT was found to be 8.069 μm. RLT were measured with the help of ImageJ software. Recast layer shown in figure 8.b was obtained for the 7th experiment and this has high Ra value which showed average recast layer thickness value of 14.815 μm. The 13th experimental run has average surface roughness value in which the recast layer thickness was obtained as 10.714 μm and is shown in figure 8.c.

Thickness of recast layer (RL) tends to increase when the increase in pulse on time (Ton) and increased energy per spark by current supplying. Thickness of RL increased with declining of Toff time. Deepness of this top liquefied zone depends upon the Ton energy and period. Higher time of Ton directs to thicker resolidified layer (17). This shows that thickness of RL increased with an increasing discharge current, Ton, energy per spark and with declining Toff time. Fig. 8.b illustrates that with larger energy release in every spark due to high value of Ton, the amount of workpiece materials which are liquefied is larger, resulting in huge amount of molten material resolidifies to shape the large average RL thickness. Fig. 8.b illustrates that the thickness of the RL is nearly twice as compared to the Fig. 8.a.

Multi objective optimization using Grey Analysis

In the current work, optimum process parameter amalgamation for maximization of hardness with minimization of surface roughness are required. Thus, Grey relational analysis (GRA) was used for finding optimum parameter combination for two or more output responses by converting into single grey relational grade (18).

Steps in GRA are: 1. Normalizing the experimental results of each performance characteristics between 0 and 1 (Higher the better or Lower the better). 2. Finding grey relational coefficient (GRC) - taken as 0.5 by giving equal weight age value for all responses.

3. Calculating single grey relational grade (GRG). 4. Selecting the optimum levels of process parameters. Table 3, 4 and 5 shows the optimization of process parameters by means of GRA.

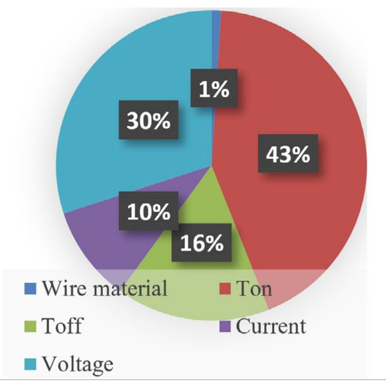
Tab.3 - Grey Relational Analysis

	Normalization		GRC			
Sl No	**SR (Min)**	**HV (Max)**	**SR (Min)**	**HV (Max)**	**GRG**	**Rank**
1	1.000	0.852	0.333	0.370	0.352	18
2	0.813	0.667	0.381	0.429	0.405	17
3	0.842	0.630	0.373	0.443	0.408	16
4	0.389	0.111	0.562	0.818	0.690	3
5	0.288	0.444	0.635	0.529	0.582	8
6	0.075	0.963	0.869	0.342	0.606	9
7	0.000	0.481	1.000	0.509	0.755	1
8	0.455	0.370	0.524	0.574	0.549	6
9	0.361	0.815	0.581	0.380	0.480	12
10	0.725	0.444	0.408	0.529	0.469	13
11	0.743	0.630	0.402	0.443	0.422	15
12	0.684	0.111	0.422	0.818	0.620	4
13	0.463	0.926	0.519	0.351	0.435	14
14	0.392	0.556	0.561	0.474	0.517	10
15	0.560	0.000	0.472	1.000	0.736	2
16	0.328	0.519	0.604	0.491	0.547	7
17	0.369	0.444	0.575	0.529	0.552	5
18	0.252	1.000	0.665	0.333	0.499	11

Tab.4 -Grey Relational Grade value for corresponding levels

Level	Wire material	Ton	Toff	Current	Voltage
1	**0.5362**	0.4459	0.5412	0.5388	0.5250
2	0.5331	**0.5943**	0.5046	**0.5493**	**0.5912**
3	-	0.5638	**0.5581**	0.5159	0.4877
Delta	0.0031	0.1484	0.0535	0.0334	0.1035
Rank	5	1	3	4	2

Fig.9 - % Contribution of process parameter



From the table 4 and figure 9 (Pie chart), the most influencing factor for the both minimization of surface roughness and maximization of hardness is identified as Ton (43%) and Voltage (30%).

Tab.5 - Optimum condition using GRA

Parameter	A: Wire material	B: Ton (μs)	C: Toff (μs)	D: Current (A)	E: Voltage (V)
Optimum levels	L1 (Coated brass wire)	Level 2 (110)	Level 3 (45)	Level 2 (3)	Level 2 (30)

Confirmation Test

The condition recommended with A1, B2, C3, D2, and E2 from GRA which is shown in table 5 is a final optimum parameter amalgamation recommended for the present Wire EDM of SS 304 block. Therefore, this condition A1, B2, C3, D2, E2 suggested by GRA was treated as multi objective optimization condition which is not available in the previously conducted 18 experiments and considered as a confirmation test. Confirmation experiment has been conducted on the SS 304 block using the optimum condition and results obtained were: minimum surface roughness- 2.516 μm and maximum hardness- 194 HV.

CONCLUSIONS

In the present work, the effect of wire electrode materials (Brass and Zinc coated brass) and electrical parameter on machinability responses was analyzed on SS 304 through Wire EDM process. Significant conclusions are:

Ton time has highest significant on surface roughness (Ra) value. Lowest Ra value was obtained with coated brass wire, Ton (105 μs), Toff (35 μs), C (1 A) and V (20 V).

Microhardness of the machined surfaces increased with increase in current, Voltage, Ton and Toff time along with coated brass wire electrode. Voltage has most significant on hardness.

Using SEM images, the recast layer thickness of the machined surface was analysed. From the images, it was concluded that higher value of Toff time with coated wire produced lesser thickness of the recast layer. Also, coated brass wire has performed well than uncoated wire in terms of machinability of this material.

Based on the GRA results, the optimized process parameter mixture to obtain together the minimum surface roughness and the maximum hardness are Coated brass wire (L1), Ton (L2) -110 μs, Toff (L3)-45 μs, Current (L2)-3 A and 30 V as gap voltage (L2).

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